Journal of Environmental Economics and Management 100 (2020) 102263

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Petrodollar recycling, oil monopoly, and carbon taxes

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ARTICLE INFO

Article history:
Received 31 March 2018
Revised 6 September 2019
Accepted 6 September 2019
Available online 19 September 2019

JEL codes:
D90
H20
Q31
Q38

Keywords:
Monopoly
Fossil energy resources
General equilibrium
Capital assets
Climate policy

ABSTRACT

Besides affecting oil rents, climate policy can have far-reaching capital market implications. We identify a new general equilibrium transmission channel of climate policy on oil extraction by an oil monopolist who accounts for the influence of oil supply on returns on own petrodollar-financed capital assets. Climate-policy-induced adjustments in capital asset holdings by the exporting country lead to postponement of extraction under a wide range of reasonable parameter settings: for the reference calibration present extraction drops by 1.28 percent for an ad valorem tax corresponding to 100$ per ton of carbon, while it increases by 0.52 percent for a competitive oil market. This contrasts with the literature on supply-side effects of climate policy which neglects these capital market implications. Concerns about carbon taxes arising from unintended climate-damaging supply reactions are alleviated.

1. Introduction

Attempts to tackle climate change and limit global carbon emissions such as the 2015 Paris Agreement naturally threaten the revenues of fossil energy resource owners like the OPEC countries. Also, the recent discussions on stranded assets and a carbon bubble emphasize far-reaching implications of climate policy for international capital markets.[1] Both dimensions are potentially important for OPEC countries, which not only export oil, but also hold large sovereign wealth funds[2] and other types of petrodollar-financed capital investments (cf. Andersen et al. (2017)). Moreover, the Saudi government's announced plan to establish a new large sovereign wealth fund and make "investments the source of Saudi government revenue, not oil" (Waldman, 2016) suggests that these countries' supply strategy increasingly rests on two pillars.

While the strategic supply-side reactions to climate policies have been extensively studied, the two-pillar nature of OPEC countries' supply behavior has not been considered in this literature so far. In doing so, we identify a new transmission channel of climate policy which can significantly alter the supply reactions to the policies by taking two additional observations into account. First, the two pillars – oil revenues and capital asset returns – are intertwined by the interplay of the oil and the capital

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[1] Cf. Caldecott et al. (2019).

[2] As of August 2016, the total volume of oil- and gas-related publicly known sovereign wealth funds was US $4205 billion (SWFI, 2018).

https://doi.org/10.1016/j.jeem.2019.102263
0095-0696/

market due to the considerable complementarity of oil (and other fossil resources) and physical capital reflected in the central role of oil in the world economy. Oil prices can heavily affect the business cycle and the resulting returns for stock- and bond-holders, especially in the major oil importing countries.[3] Also, long-term paths of economic growth and capital accumulation are affected by the availability of oil.[4] In turn, fast-growing economies like China have a significant impact on oil demand and prices.[5] Second, despite many suppliers of oil, the global market share of 42% (in 2013) of OPEC suggests a significant degree of concentration in the oil market, especially in the longer run.[6]

To represent the multi-dimensional interaction between the oil market, the capital market, and oil market power we build on the scarce literature on fossil resource monopoly in general equilibrium.[7] We introduce climate policy into the framework of Marz and Pfeiffer (2015). The “capital asset motive”, which was newly identified therein, results from the capital income pillar pointed out before and from the influence of resource supply on capital returns.[8] Specifically, we apply a two-period general-equilibrium model of the world economy with oil, capital, and labor as production inputs and endogenous capital formation. The interest rate and savings, which determine physical capital accumulation,[9] are endogenously affected by oil supply. The resulting capital stock drives oil demand and revenues for the exporting country. These relationships are known to the government, or the state-owned oil company, of the oil-rich country, which finances its households' consumption by exporting oil and investing its savings in the importing country, which produces final goods.[10] We focus on a monopolist as the opposite to perfect competition, and abstract from extraction costs and backstop substitutes for simplicity.

The new transmission channel of climate policy arises from the asset motive and endogenous savings. First, the impact of the introduction or increase of a future carbon tax in the importing country on oil profits incentivizes the oil exporter to accelerate extraction, exacerbating climate damages – an outcome coined the “Green Paradox” by Sinn (2008). Second, however, facing the future oil income loss and overall oil asset devaluation, the oil-rich country saves more to smooth consumption. Larger future asset holdings strengthen the complementarity-driven influence of oil supply on the exporting country's future capital income. The resulting incentive to postpone oil supply can be strong enough to overcompensate the first acceleration incentive.

The literature on the supply-side effects of climate policies has thoroughly examined whether, and when, the extraction of fossil fuels is accelerated or not, and whether this leads to larger climate damages. A wide range of aspects and mechanisms have been considered, like more detailed representations of extraction costs, perfect and imperfect substitutes, dirty substitutes like coal, or the interaction between geographical and intertemporal leakage.[11] In most of these contributions, resource market power is not crucial. For example, van der Ploeg and Withagen (2012) and Grafton et al. (2012) both conclude that market power does not fundamentally change their results from the respective competitive market case. More recently, however, Andrade de Sá and Daubanes (2016) pointed out that climate policies can be neutral with respect to monopolistic resource extraction under permanent limit pricing (cf. Hoel (1978, 1983)). Gilbert and Goldman (1978), van der Meijden and Withagen (2016), and van der Meijden et al. (2018) also show that with phase(s) of limit pricing due to resource market power with a substitute, policies like a subsidy for the substitute can induce postponement instead of acceleration of extraction. We also contribute to the understanding of the role of market power for the supply-side reaction, without considering extraction costs, backstops, or limit pricing. Instead, we focus on capital-market implications of market power in general equilibrium, which the aforementioned literature does not take into account.[12]

[3] Cf. Hamilton (1983, 2013), Kang et al. (2014), Cunado and Perez de Gracia (2014). Kilian (2009) points out that the magnitude of macroeconomic effects of an oil price shock depends on whether it is driven by the supply side, the demand side, or demand-side responses to an anticipated supply shock.

[4] Cf., from an empirical perspective, Berk and Yetkiner (2014) and Stern and Kander (2012); from a theoretical perspective, see Stiglitz (1974).

[5] Cf. Kilian and Hicks (2013) and Fouquet (2014).

[6] The market share of OPEC is likely to rise over time again. For example, under the 450 ppm carbon scenario the International Energy Agency expects the OPEC market share to rise to 48% in 2040 (OECD, 2014, p. 115, Table 3.5).

[7] Cf. Moussavian and Samuelson (1984) or Hillman and Long (1985) without climate policy.

[8] Marz and Pfeiffer (2015) show (without discussing climate policy) that, in contrast to the conventional partial equilibrium view (cf. Stiglitz, 1976), the interaction of the capital and the resource market already has implications for the supply decision of a resource owner with market power (cf. also Bonanno, 1990). In particular, the monopolist takes into account the influence of resource supply on the return of her own capital assets, which are invested in the resource importing countries, and on capital accumulation with resulting feedbacks on capital and resource demand. This framework still leads to a Hotelling rule, which is extended by a capital income component. Anderson et al. (2018) criticize the classical Hotelling approach as oversimplified pointing to the geophysical constraints and complex cost structures in oil extraction. However, they show that long-term planning of drilling more strongly depends on the development of market prices and intertemporal arbitrage considerations, and is, therefore, more in line with the Hotelling reasoning. By focusing on long-term extraction decisions with discrete periods of several decades, our model is much more closely related to the long-term planning of oil drilling in Anderson et al. (2018) than to short-term supply decisions for explored and open oil fields.

[9] We do not exclude negative savings. Countries can also borrow from each other.

[10] Higgins et al. (2006) conclude that about half of the oil exporting countries' profits in the 2000s were invested in foreign assets and over different channels ended up in the U.S.

[11] For literature overviews, see Jensen et al. (2015), van der Ploeg and Withagen (2015), and van der Werf and Di Maria (2011). The theoretical observations for the relevance of the Green Paradox are mixed, and so are the results from the few empirical studies. Di Maria et al. (2014) confirm the underlying mechanisms for the case of the reaction of coal supply to the introduction of the acid rain program in the U.S. But for coal, neither market power, nor capital assets play the prominent role, as in the case of oil. Curuk and Sen (2015) find an increase in oil trade as a reaction to raised R&D spending in renewable energy, but they also neglect the role of capital assets.

[12] In partial equilibrium, our setting of monopolistic oil supply would necessarily lead to acceleration of extraction, whereas with the new, capital asset based transmission channel of climate policy we find that extraction can still be postponed.

The focus on the role of market power also differentiates our work from the literature on supply-side reactions to climate policies in general equilibrium (Long, 2015; Eichner and Pethig, 2011; Smulders et al., 2012; Long and Stähler 2018).[13] Van der Ploeg (2016) and, in particular, van der Meijden et al. (2015) who apply frameworks very similar to ours, except for their competitive oil market, are the closest to our work. Van der Meijden et al. (2015) first show that the general equilibrium adjustment of the interest rate to oil supply changes can attenuate the supply-side reaction to climate policy. This effect is very small, and also present (and still very small) in our monopolistic supply setting. Second, they obtain a "tiny" postponement of extraction under quite extreme parameter settings only by assuming asymmetric preferences of the oil-exporting and oil-importing country. In this case, climate policy also directly affects the interest rate by the induced redistribution of resource rents and the according adjustment of the capital market. With market power and the capital asset based transmission channel we do not have to assume asymmetric preferences for climate policy to induce postponement of extraction. We therefore focus on symmetric preferences. By considering the respective extreme of monopoly or perfect competition, van der Meijden et al. (2015) and our contribution are complementing each other, but we point out a completely different transmission channel of climate policies.[14]

In the numerical analysis, postponement of extraction can be observed for a wide range of plausible parameter settings. In the reference case, present extraction drops by 1.28 percent for a future ad valorem carbon tax corresponding to a carbon price of about 100 dollars per ton of carbon.[15] By contrast, present extraction changes by 0 percent if the monopolist neglects the new capital asset channel and increases by 0.52 percent for a competitive oil market. Overall, we show that (even) an over time increasing carbon tax can be a viable policy option in contrast to conventional partial equilibrium analyses of climate policy instruments.

We present our model in Section 2 and characterize the monopolist's extraction decision in Section 3. In Section 4 we identify and interpret the mechanism that may lead to postponement of extraction, complemented by a numerical analysis in Section 4.3. In Section 5 we discuss our results with respect to the empirical evidence on the elasticity of oil demand and with respect to the oil market structure by introducing a competitive fringe of oil producing firms. Section 6 concludes.

2. Model

We consider a general equilibrium model with a finite time horizon of two periods $t \in 1,2$ and two countries $m \in \{E, I\}$. The oil exporting country E supplies oil to the final goods producers in country I in exchange for consumption goods, which are numeraire.

2.1. Oil supply and final goods production

Country E's government, or the state-owned oil company, monopolistically controls the world supply of oil R_t from the given stock $\overline{S}$. Since oil is extracted at zero costs,[16] oil exports yield $\pi^{\tau}_{tE} = \widetilde{p}_t R_t$ with $\widetilde{p}_t$ denoting the producer price for oil net of the carbon tax τ_t levied by country I. For simplicity, we assume $\tau_1 = 0$. In the following, we focus on an ad valorem tax, but point out when a unit resource tax would have different implications.

In country I, final goods are produced competitively using physical capital K_t, oil R_t, and labor $L_t = L = 1$ as inputs in constant returns to scale technology $F = F(K_t, R_t)$ with $F_R, F_K > 0$, $F_{RR}, F_{KK} < 0$, and $F_{KR} > 0$.[17] With consumer oil price p_t and the capital rent i_t, the first-order conditions for the final good producers' optimal factor use (implicitly) define oil demand R^d_t and capital demand K^d_t[18]:

$$\frac{\partial F(K_t, R^d_t)}{\partial R^d_t} = p_t \tag{1}$$

[13] Hassler et al. (2010) analyze climate policy in general equilibrium with resource market power, too. But they consider neither a dynamic setting nor general equilibrium effects of climate policy on supply.

[14] The households' savings reaction in the oil-rich country is also related the redistribution of oil rents. Yet, the capital-asset based transmission channel does not arise from adjustments of the overall capital market equilibrium, but from the relevance of the oil exporting country's savings increase due to the asset motive. With symmetric preferences we exclude the according transmission channel from van der Meijden et al. (2015) and the related *additional* influences on the monopolist's supply. In particular, the supply policy of an oil monopolist in comparison to the competitive market crucially depends on the price elasticity of demand and its development over time (cf. Stiglitz, 1976). So, climate policies may affect the monopolist's supply policy by altering the price elasticity of demand. In our setting, with symmetric preferences, climate policies are neutral with respect to the overall capital market equilibrium and do not have any such direct influence on oil demand. The price elasticity of demand, of course, changes with adjustments in the monopolist's supply path. This, however, affects our results only quantitatively but cannot induce postponement of supply.

[15] This tax level is in line with estimates for the social cost of carbon by Anthoff et al. (2009) or Nordhaus (2010) and lies roughly in the middle of the wide range of estimates.

[16] See Appendix D for an extension with exploration costs.

[17] We assume flexible wages under full employment here. Subscripts to the production technology F denote the first or second derivative with respect to production factor(s) indicated.

[18] The superscript "s" indicates *supply*, while superscript "d" means *demand*.

$$\frac{\partial F(K_t^d, R_t)}{\partial K_t^d} = i_t \tag{2}$$

2.2. Households and capital supply

Households in countries E and I have symmetric homothetic preferences represented by the life-time utility function $U(c_{1\,\mathrm{m}}, c_{2\,\mathrm{m}}) = u(c_{1\,\mathrm{m}}) + \beta u(c_{2\,\mathrm{m}})$ with $u'(.) > 0$ and $u''(.) < 0$ and the utility discount factor $\beta < 1$ for both countries. They have rational expectations with respect to income streams and market interest rates i_t. Households maximize life-time utility from consumption subject to country-specific budget constraints. They optimize their intertemporal consumption profile by saving and investing $s_{1\,\mathrm{m}}$ from first period income.[19] In the first period, households hold an exogenously given, non-negative capital endowment $s_{0\,\mathrm{m}}$. We assume a constant population size of 1 for both countries.

In country E, the government benevolently distributes the post-tax resource revenue, or profits, π_t^τ to the households. The budget constraints for both periods are given by

$$c_{1E} + s_{1E} = y_{1E} \quad \text{with} \quad y_{1E} = \pi_{1E} + (1 + i_1)s_{0E} \tag{3}$$

$$c_{2E} = \pi_{2E}^\tau + (1 + i_2)s_{1E} \tag{4}$$

In country I, the representative household receives the residual profits π_{tI} after remuneration of capital and oil as labor income: $\pi_{tI} = F(K_t, R_t) - p_t R_t - i_t K_t$. Additionally, there is a lump-sum transfer of the tax revenue T_2 collected from the resource tax τ_2. Therefore, the budget constraints for country I households are $c_{1I} + s_{1I} = y_{1I}$ – again with $y_{1I} = \pi_{1I} + (1 + i_1)s_{0I}$ – and $c_{2I} = \pi_{2I}^\tau + (1 + i_2)s_{1I}$ with $\pi_{2I}^\tau = \pi_{2I} + T_2$.

The optimal intertemporal consumption profile of households is characterized by the respective familiar Euler equation $u'(c_{1\,\mathrm{m}}) = \beta(1 + i_2)u'(c_{2\,\mathrm{m}})$. The Euler equation implicitly defines optimal savings $s_{1\,\mathrm{m}}$ as a function of period incomes $y_{1\,\mathrm{m}}$ and $\pi_{2\,\mathrm{m}}^\tau$, and the interest rate i_2, which households take as given (cf. Appendix A.1):

$$s_{1m} = s_{1m}(y_{1m}, \pi_{2m}^\tau, i_2) \quad \text{with} \quad \frac{\partial s_{1m}}{\partial y_{1m}} > 0, \quad \frac{\partial s_{1m}}{\partial \pi_{2m}^\tau} < 0, \quad \frac{\partial s_{1m}}{\partial i_2} \gtrless 0 \tag{5}$$

Since we assume homothetic consumption preferences, the marginal savings reactions with respect to changes in period incomes are independent of the household's income level. They are determined only by the discount factor β, the intertemporal elasticity of substitution $\frac{1}{\eta}$, and the market interest rate i_2. As will be shown in Section 2.3, the market interest rate is independent of the resource tax for symmetric countries, that is, the case where both countries have the same time preferences. The marginal saving propensities with respect to changes in period incomes therefore are also independent of the resource tax and completely equivalent to the no-tax case.

World capital supply in both periods derives from aggregate savings of households. For the first period, capital supply is given by the endowments: $K_1^s = s_{0E} + s_{0I}$. Second period capital supply is endogenously determined by aggregated savings of households in both countries. Since the existing capital stock is available for consumption (and savings) at the end of each period without depreciation, positive capital accumulation implies $s_{1E} + s_{1I} > K_1$. For symmetric homothetic preferences, second period capital supply is a function of resource supply and the interest rate i_2 only (cf. Appendix A.2):

$$K_2^s = K_2^s(R_1, R_2, i_2) \quad \text{with} \quad \frac{\partial K_2^s}{\partial R_1} > 0, \frac{\partial K_2^s}{\partial R_2} < 0, \frac{\partial K_2^s}{\partial i_2} > 0 \tag{6}$$

An increase in R_1, holding R_2 fixed[20], raises first period (global) income which leads households to save more for reasons of consumption smoothing (cf. (5)). An increase in R_2 reduces aggregate savings for the same reason. An increase in i_2 unambiguously raises aggregate savings, ceteris paribus, because the income effects induced imply a redistribution of income between countries, which cancels out for symmetric homothetic preferences. Similarly, aggregate capital supply does not depend on the future period's resource tax levied in country I. By raising this tax, country I, ceteris paribus, captures a larger share of the resource rents from country E. However, since this constitutes a pure redistribution of rents, the savings reactions exactly cancel out again.

2.3. Conditional market equilibrium

We now consider the overall equilibrium of the markets for oil, capital, and final goods conditional on oil supply in both periods (R_1, R_2). Since (1) and (2) must hold simultaneously in equilibrium, resource and capital demand can be shown to be

[19] We generally do not exclude negative savings.

[20] Note that we do not impose the assumption of a binding resource constraint here.

functions of the oil price and the capital rent only. The *resource market equilibrium* and the *capital market equilibrium* in both periods then are characterized by the market-clearing conditions

$$R_t^d(p_t, i_t) = R_t^s \quad \text{for periods t} = 1, 2 \tag{7}$$

$$K_1^d(p_1, i_1) = K_1 = s_{0E} + s_{0I} \tag{8}$$

$$K_2^d(p_2, i_2) = K_2^s(R_1, R_2, i_2) \tag{9}$$

with capital supply from endowments in period 1 and from (6) in period 2. For the *final goods market*, aggregate consumption (and savings) has to equal aggregate consumption possibilities, which are given by production and the capital stock in both periods: $c_{1E} + c_{1I} + K_2 = F(K_1, R_1) + K_1$ and $c_{2E} + c_{2I} = F(K_2, R_2) + K_2$. By Walras' law these conditions will hold if the resource market and the capital market are in equilibrium.

This set of equations implicitly defines equilibrium oil prices, capital rents, and the equilibrium future capital stock as functions of oil supply in both periods only. A comparative statics analysis allows us to observe this more directly and to examine the influence of oil supply on the equilibrium outcomes. For period 1, by totally differentiating (7) and (8), accounting for (1) and (2), and solving the two resulting equations together, we find that in the conditional market equilibrium $p_1 = p_1(R_1)$ and $i_1 = i_1(R_1)$ with

$$\frac{dp_1}{dR_1} = \frac{\partial p_1}{\partial R_1} < 0 \tag{10}$$

$$\frac{di_1}{dR_1} = \frac{\partial i_1}{\partial R_1} > 0 \tag{11}$$

due to the concavity of the production technology and the complementarity of capital and oil. In period 2, the equilibrium relationships are more complex due to the endogenous adjustment of the capital stock. By totally differentiating (6), (7), and (9), taking into account (1) and (2), and solving the resulting equations together (cf. Appendix A.3), we observe that $p_2 = p_2(R_1, R_2)$, $i_2 = i_2(R_1, R_2)$, and $K_2 = K_2(R_1, R_2)$ with[21]:

$$\frac{dp_2}{dR_1}|_{R_2} = \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_1}|_{R_2} > 0, \quad \frac{dp_2}{dR_2}|_{R_1} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2}|_{R_1} < 0 \tag{12}$$

$$\frac{di_2}{dR_1}|_{R_2} = \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_1}|_{R_2} < 0, \quad \frac{di_2}{dR_2}|_{R_1} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2}|_{R_1} > 0 \tag{13}$$

$$\frac{dK_2}{dR_1}|_{R_2} > 0, \quad \frac{dK_2}{dR_2}|_{R_1} \gtrless 0 \tag{14}$$

Considering (12), oil supply R_2 affects p_2 on the one hand directly ($\frac{\partial p_2}{\partial R_2} < 0$), and on the other hand via its effect on the capital stock K_2 and the complementarity of oil and capital ($\frac{\partial p_2}{\partial K_2} > 0$). Oil supply R_1 also influences p_2 but only indirectly via its separate effect on K_2. For (13) the analogue reasoning applies. Note that an increase in R_1 raises global income in the present but does not change the interest rate i_2 directly. Thus, by (5), it unambiguously increases aggregate savings (and K_2). In contrast, an increase R_2 boosts future income, reducing savings (cf. (5)), and raises the interest rate i_2 by the complementarity of oil and capital, leading to a counteracting substitution effect. Hence, the influence of R_2 on K_2 is generally ambiguous.

With a binding resource constraint, market prices and the second-period capital stock are functions of the oil supply *path*, and, therefore, effectively of supply in one period only. Taking R_2 as choice variable, the corresponding equilibrium relationships can easily be derived by using $dR_1 = -dR_2$ and (12), (13), and (14):

$$\frac{dp_2}{dR_2} = \frac{dp_2}{dR_1}|_{R_2}\frac{dR_1}{dR_2} + \frac{dp_2}{dR_2}|_{R_1} = \frac{\partial p_2}{\partial R_2} + \frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2} < 0 \tag{15}$$

$$\frac{di_2}{dR_2} = \frac{di_2}{dR_1}|_{R_2}\frac{dR_1}{dR_2} + \frac{di_2}{dR_2}|_{R_1} = \frac{\partial i_2}{\partial R_2} + \frac{\partial i_2}{\partial K_2}\frac{dK_2}{dR_2} > 0 \tag{16}$$

$$\frac{dK_2}{dR_2} = \frac{dK_2}{dR_1}|_{R_2}\frac{dR_1}{dR_2} + \frac{dK_2}{dR_2}|_{R_1} \gtrless 0 \tag{17}$$

For a more detailed derivation of the comparative statics results see Appendix A.3.

[21] We use the notation $\frac{dp_2}{dR_2}|_{R_1}$ to clarify that we consider, for example, a change in R_2 while taking R_1 as fixed. In contrast, by $\frac{\partial p_2}{\partial R_2}$ we denote the pure partial equilibrium effect of a change in R_2 on the market price.

3. The Monopolist's optimal resource extraction

To examine the supply-side reaction to climate policy (in Section 4) we first summarize the extraction behavior of country E's government, or state-owned oil company. The monopolist accounts for the influence of her supply on the world market equilibrium in both periods, that is, the conditional market equilibrium from section 2.3.[22] Hence, the monopolist acts as a Stackelberg leader. With state-controlled oil supply, like in most OPEC countries, we assume that the monopolist plans oil extraction benevolently in order to maximize life-time utility of households in country E:

$$\max_{R_1,R_2} u(c_{1E}) + \beta u(c_{2E}) \quad \text{s.t.} \quad R_1 + R_2 \leq \overline{S} \tag{18}$$

subject also to the budget constraints (3) and (4) and the conditional market equilibrium relationships laid out in Section 2.3.[23] Already Stiglitz (1976) and Tullock (1979) discuss that the marginal value of the resource to a monopolist may be negative if she has to exhaust the stock within a finite period of time, and that, in this case, the monopolist would leave the excess resource in the ground. Hence, we do not impose the stricter assumption of a binding resource constraint in (18) but allow for incomplete extraction.

3.1. Complete extraction

We start with the more standard case in which oil is sufficiently scarce relative to oil demand from final goods production so that the entire oil stock is extracted. With $dR_1 = -dR_2$ and (15) and (16) the extraction decision turns into a one-dimensional problem over the timing of extraction only. Substituting the Euler equation into the first-order condition and simplifying yields the modified Hotelling rule[24]

$$(1+i_2)\left[p_1 + \frac{\partial p_1}{\partial R_1}R_1 + \frac{\partial i_1}{\partial R_1}s_{0E}\right] = \widetilde{p}_2 + \frac{d\widetilde{p}_2}{dR_2}R_2 + \frac{di_2}{dR_2}s_{1E} \tag{19}$$

While (19) is a standard non-arbitrage condition for the trade-off between current and future supply, the benevolent monopolist trades off more than just marginal revenue, even without extraction costs (cf. Marz and Pfeiffer (2015)). In addition to *marginal revenue* before taxes MR_t, the *marginal resource value* MV_t (net of taxes) includes the marginal effect of oil supply on the return on country E's capital assets[25]:

$$\begin{aligned} MV_t &= \widetilde{p}_t + \frac{d\widetilde{p}_t}{dR_t}R_t + \frac{di_t}{dR_t}s_{(t-1)E} = (1-\tau_t)MR_t + \frac{di_t}{dR_t}s_{(t-1)E} \\ &= (1-\tau)p_t\left[1 - \frac{1}{\epsilon_{R_t,p_t}}\right] + \frac{di_t}{dR_t}s_{(t-1)E} \end{aligned} \tag{20}$$

This gives rise to an additional, so called capital asset supply motive, which differentiates the supply behavior of the omniscient, benevolent monopolist from her naïve partial equilibrium counterpart for example in Stiglitz (1976).[26] Moreover, our monopolist also accounts for the endogeneity of the second-period capital stock with respect to her supply decision according to (17), which is included in the equilibrium market price reactions in period 2. This also modifies the supply pattern compared to that of a naïve partial equilibrium monopolist, in particular since it effectively reduces (increases) the price elasticity of oil demand ϵ_{R_t,p_t} for $\frac{dK_2}{dR_2} < 0$ ($\frac{dK_2}{dR_2} > 0$). The relationship of MV_t to the demand elasticity ϵ_{R_t,p_t} is illustrated by the last transformation in (20).[27]

[22] The monopolist's optimal extraction decision without a carbon tax, which crucially depends on her awareness of the general equilibrium feedbacks, is discussed in detail for the case of a binding resource constraint by Marz and Pfeiffer (2015). Here, we also include the case of incomplete extraction.

[23] See Appendix A.4 for a more extensive presentation of the monopolist's optimization problem.

[24] Note that there is no derivative of the market discount factor $(1 + i_2)$ appears in the modified Hotelling rule, although the oil monopolist accounts for her influence on the capital return i_2. The reason is that the discount factor $(1 + i_2)$ derives from the separate savings decision of the households which act as price takers on the capital market(cf. Section 2.2).

[25] We have $\frac{dp_1}{dR_1} = \frac{\partial p_1}{\partial R_1}$ from (10), $\frac{di_1}{dR_1} = \frac{\partial i_1}{\partial R_1}$ from (11). For period 2, we have $\frac{d\widetilde{p}_2}{dR_2} = (1-\tau_2)\frac{dp_2}{dR_2}$ for an ad valorem and $\frac{d\widetilde{p}_2}{dR_2} = \frac{dp_2}{dR_2}$ for a unit resource tax with $\frac{dp_2}{dR_2}$ from (15) and $\frac{di_2}{dR_2}$ from (16).

[26] With the asset motive, it does not only depend on the development of the price elasticity of demand ϵ_{R_t,p_t} over time but also on the development of marginal resource value in terms of capital income how fast the monopolist exhausts the resource stock. The monopolist may accelerate, or slow down extraction compared to her naïve counterpart, or the competitive market (cf. Marz and Pfeiffer, 2015).

[27] For period 2, our notion of the elasticity also accounts for the endogenous adjustment of the capital stock and the resulting changes in the demand curve.

3.2. Incomplete extraction

If the oil stock is relatively abundant from the monopolist's perspective, she leaves some oil underground. Supply in both periods is chosen independently and is characterized by two first-order conditions following from (18):

$$(1+i_2)MV_1 + \Psi = 0 \quad \text{with} \quad \Psi = \left[(1-\tau)\frac{\partial p_2}{\partial K_2}R_2 + \frac{\partial i_2}{\partial K_2}s_{1E}\right]\frac{dK_2}{dR_1}|_{R_2} \lesseqgtr 0 \tag{21}$$

$$MV_2^{inc} = (1-\tau)MR_2^{inc} + \frac{di_2}{dR_2}|_{R_1}s_{1E} = 0 \quad \text{with} \quad MR_2^{inc} = p_2 + \frac{dp_2}{dR_2}|_{R_1}R_2 \tag{22}$$

With incomplete extraction, the monopolist supplies only as long as the marginal value is positive to her. The future (marginal) value of oil is MV_2^{inc}, which is defined similarly to (20). The superscript "inc" for "incomplete extraction" indicates that in this case the influence of future supply on the conditional market equilibrium is different (cf. (12), (13), and (14)). Complete depletion of the oil stock depends on MV_2^{inc} (not on MV_2)[28]. For $MV_2^{inc} > 0$, the resource constraint binds, and optimal supply follows the Hotelling rule (19).[29] The present (marginal) value of oil is given by MV_1, as in the complete extraction case (cf. (10), (11)). However, present supply R_1 also increases the future capital stock K_2 (cf. (14)), and thereby affects both future income streams. This is captured by Ψ, and adds to the (marginal) value of first-period supply.[30] Overall, since K_2 and savings s_{1E} are endogenous with respect to supply, the optimal choices of R_1 and R_2 are interdependent and not entirely static.

4. Policy analysis

We now discuss the benevolent monopolist's supply reaction to future climate policy for complete and incomplete extraction. Using comparative statics we show that a marginal increase in the future carbon tax may induce postponement of extraction due to the asset motive. We numerically illustrate the drivers and the significance of our observations.

4.1. Supply reaction to climate policy – complete extraction

For the supply reaction in the complete extraction case, we totally differentiate (19) with respect to R_2 and τ_2 taking into account $dR_1 = -dR_2$ by the binding resource constraint and (10), (11), (15), and (16). Evaluating the resulting comparative statics for an optimal oil supply path (R_1^*, R_2^*)[31] we obtain the following proposition.

Proposition 1. *With complete extraction, the reaction of the equilibrium extraction path to an increase of the future ad valorem tax is given by*

$$\frac{dR_2^*}{d\tau_2} = \frac{-MR_2 + \frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2}}{\frac{d[(1+i_2)MV_1]}{dR_2} - \frac{dMV_2}{dR_2}} \gtreqless 0 \tag{23}$$

The monopolist postpones extraction if $\frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2} > MR_2$ *and accelerates extraction if* $\frac{di_2}{dR_2}\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}}\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2} < MR_2$.

Note that the denominator of (23) is always positive due to the second-order condition of optimal supply (cf. Appendix A.4). It captures how the Hotelling condition (19) changes with a marginal adjustment of the extraction path.[32] In particular, the denominator includes changes in the interest rate i_2 which are induced by the supply reaction. This "feedback effect" also plays a role in the competitive case (van der Meijden et al., 2015) and always attenuates the supply reaction (Cf. (16)). In fact, such "feedback effects" always influence the supply reaction only quantitatively. By contrast, the numerator of (23) characterizes whether the monopolist wants to accelerate or postpone extraction upon the tax increase. It captures the *direct* effects of the tax change on both components of MV_2 from (20): the resource income component given by the marginal resource revenue MR_2 (before taxes) and the capital income component given by the asset motive. Since the conditional market equilibrium does not directly depend on the tax for symmetric preferences, the tax increase has no direct effect on (10), (11), (15), and (16), and therefore also does not affect the demand elasticity.

First, the tax increase influences the resource income component which is captured by the marginal resource revenue before taxes MR_2 in the numerator of (23) for the ad valorem tax. For a unit resource tax, we would have just -1 instead (cf. Appendix B.3). If MR_2 is positive, both tax policies have the same qualitative effect: an increase in the resource tax reduces

[28] Cf. the more formal analysis of the optimization problem (18) in Appendix A.4.

[29] Technically, we can derive Hotelling rule (19) from conditions (21) and (22) by equating both, subtracting Ψ from MV_2^{inc}, using (15), (16), and $dR_1/dR_2 = -1$ by the resource constraint.

[30] Due to $\frac{\partial p_2}{\partial K_2} > 0$ and $\frac{\partial i_2}{\partial K_2} < 0$, Ψ is unambiguously positive only for negative s_{1E}.

[31] The asterisk "*" in R_2^* indicates the monopolist's optimal extraction path (R_1^*, R_2^*).

[32] We have $\frac{d[(1+i_2)MV_1]}{dR_2} - \frac{dMV_2}{dR_2} = \frac{di_2}{dR_2}MV_1 - (1+i_2)\frac{dMV_1}{dR_1} - \frac{dMV_2}{dR_2} > 0$.

marginal oil revenue, and thereby creates an incentive for the monopolist to shift resources from the future to the present. This is the familiar Green Paradox result.[33]

Second, due to the asset motive, there is an additional effect of the tax on the capital income component. This is captured by the second term in the numerator and arises for both, the ad valorem and the unit tax (cf. Appendix B.3). A higher tax for a given consumer resource price p_2[34] redistributes oil income from country E to country I ($\frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2} < 0$). This redistribution is completely neutral with respect to K_2, but not with respect to individual savings in both countries. Households in country E – having rational expectations – react to the future income loss by *increasing* savings for reasons of consumption smoothing ($\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} < 0$, cf. (5)).[35] With the asset motive, larger savings increase the marginal return on oil supply in terms of the capital income gain. Hence, there is a leverage effect which unambiguously incentivizes the monopolist to shift supply to the future.[36] This capital asset based transmission channel of climate policy does not rely on positive savings in country E. The supply reaction results from the policy-induced *change* in savings which is the same for negative and positive savings ($\frac{\partial s_{1E}}{\partial \pi_{2E}^{\tau}} \frac{\partial \pi_{2E}^{\tau}}{\partial \tau_2} > 0$).

Overall, if MR_2 is positive, there are two counteracting effects, so that the net marginal tax effect is generally of ambiguous sign. If the strengthening of the asset motive from the savings reaction dominates the reduction in the marginal resource revenue, the future marginal resource value to the monopolist MV_2 will increase. The monopolist will postpone extraction (and vice versa). This supply reaction is contrary to the acceleration reaction of a monopolist in partial equilibrium without extraction costs and substitute or backstop. It is also opposite to the supply reaction of a more naïve monopolist in general equilibrium who does not pursue the asset motive.

The asset based transmission channel of climate policy fundamentally differs from the general equilibrium effect of climate policy which van der Meijden et al. (2015) point out. In their case, competitive firms postpone extraction only if the policy induced redistribution of oil rents affects the capital market equilibrium due to *asymmetric* preferences between the exporting and importing countries. If we introduced asymmetric preferences, there would be an *additional* direct effect of the tax increase in the numerator of (23) running via the induced change in K_2.[37] Moreover, the supply policy of a monopolist, in principle, crucially depends on the demand elasticity (Stiglitz, 1976). However, the asset based transmission channel of climate policy does not hinge on climate policy directly inducing changes in the price elasticity of oil demand.[38] The tax increase does not affect the conditional market equilibrium for symmetric countries, and therefore does not change the demand elasticity directly. Only when resource supply starts to adjust, the demand elasticity changes. This "feedback effect" is captured in the denominator of (23), and alters the supply reaction quantitatively but not qualitatively, i.e. cannot induce postponement without the asset term in the numerator.

4.2. Supply reaction to climate policy – incomplete extraction

For the supply reaction in the incomplete extraction case, we totally differentiate the first-order conditions (21) and (22) with respect to R_1, R_2, and τ_2. Summarizing terms and solving the resulting equations together, we obtain the following proposition

Proposition 2. *With incomplete extraction, the reaction of equilibrium oil supply to an increase of a future* ad valorem *tax is given by*

$$\frac{dR_1^*}{d\tau_2} = \frac{\frac{dR_1^*}{d\tau_2}|_{R_2} + \frac{dR_1^*}{dR_2}\frac{dR_2^*}{d\tau_2}|_{R_1}}{1 - \frac{dR_1^*}{dR_2}\frac{dR_2^*}{dR_1}} \tag{24}$$

$$\frac{dR_2^*}{d\tau_2} = \frac{\frac{dR_2^*}{d\tau_2}|_{R_1} + \frac{dR_2^*}{dR_1}\frac{dR_1^*}{d\tau_2}|_{R_2}}{1 - \frac{dR_1^*}{dR_2}\frac{dR_2^*}{dR_1}} \tag{25}$$

First and second period supply react to the tax change, and may both increase or decrease.

[33] Recall that MR_2 for the benevolent monopolist in general equilibrium not only includes the direct own price effect of resource supply but also the indirect price effect via the endogeneity of K_2 as we have $\frac{dp_2}{dR_2}$ from (15) instead of $\frac{\partial p_2}{\partial R_2}$.

[34] Recall that the numerator measures the direct effect of the tax, i.e. for a *given* extraction path.

[35] In turn, the households in country I save less due to the higher tax revenue. Thereby, they exactly compensate for the larger capital supply from country E so that K_2 is unaffected by the tax increase.

[36] This postponement incentive must not be confounded with the endogenous adjustment of the market interest rate in general equilibrium, which occurs as soon as the tax policy triggers a change in the extraction path. The latter is known from the competitive market case in van der Meijden et al. (2015) and is also present in our monopoly setting, as pointed out before.

[37] This would work against or towards extraction postponement depending on the preference structure, just as in van der Meijden et al. (2015).

[38] This is also illustrated by the unit tax case, for which we have −1 in contrast to MR_2 in the numerator of (23) so that the sign of the numerator does not depend on the demand elasticity. Similarly, assuming iso-elastic demand does not change the comparative statics in (23).

For details, see Appendix A.5.[39] The denominator captures the "feedback effects" of oil supply changes on the first-order conditions (21) and (22). Evaluated for optimal supply (R_1^*, R_2^*),[40] the denominator must be positive due to the second-order conditions for optimal supply (cf. Appendix A.4.2). In the following, we again focus on the numerators.

For both, R_1^* and R_2^*, the tax effect derives from two elements. First, there is a "direct" tax influence on period oil supply, given by the first term in the respective numerator. Second, the tax also influences period supply via the direct tax effect in the other period and the interdependence of period oil supplies. The latter is due to the endogeneity of K_2 with respect to both, R_1 and R_2 (cf. (14)), and captured by the (generally ambiguous) terms $\frac{dR_1^*}{dR_2}$ and $\frac{dR_2^*}{dR_1}$. The overall tax effects for both, R_1^* and R_2^*, are generally of ambiguous sign. So, similarly to the complete extraction case, postponement or acceleration of extraction – defined now by the climate policy reaction in period 1 – is in principle possible. However, now cumulative extraction may increase or decrease, too.

The direct effect of future taxation on R_1 ($\frac{dR_1^*}{d\tau_2}|_{R_2}$) results from Ψ (cf. (21)) and is negative: a higher tax reduces the (marginal) value of R_1 in terms of the capital-accumulation-driven oil income gains (for an ad valorem, not for a unit tax), and in terms of future capital income, because the tax increase again triggers a rise of savings s_{1E} to smooth consumption.[41] In contrast, the direct tax effect on R_2, given by $\frac{dR_2^*}{d\tau_2}|_{R_1}$, is unambiguously positive for positive savings s_{1E}. In this case, $MR_2^{inc} < 0$ by (22), and a tax increase reduces the negative oil income component in MV_2^{inc} for an ad valorem tax (not for a unit tax). At the same time, the tax increase strengthens the asset motive by the induced savings increase, as pointed out before (cf. Section 4.1). For negative savings, even the direct tax effect on R_2^* is ambiguous. While still strengthening the asset motive, the tax reduces the oil income component in MV_2^{inc} since $MR_2^{inc} > 0$ must hold. Overall, the novel transmission channel of climate policy via the adjustment of capital assets and via the endogeneity of capital returns with respect to oil supply from the complete extraction setting (cf. Section 4.1) completely carries over and is still relevant in the incomplete extraction case.

4.3. Numerical analysis

To further examine the supply reaction numerically, we assume CES technology $F(K_t, R_t) = A[\gamma K_t^{\frac{\sigma-1}{\sigma}} + \lambda R_t^{\frac{\sigma-1}{\sigma}} + (1-\gamma-\lambda)L^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}}$ with total factor productivity $A > 0$ and constant elasticity of substitution σ. The period utility function is symmetric and homothetic: $u(c_{tm}) = \frac{c_{tm}^{1-\eta}-1}{1-\eta}$ for $\eta \neq 1, \eta > 0$ and $u(c_{tm}) = \ln c_{tm}$ for $\eta = 1$ where $1/\eta$ is the constant elasticity of intertemporal substitution. The influence of the factor endowments K_1 and $\bar{S}$, the households' utility parameters β and η, and the distribution of the capital asset endowment $\frac{s_{0E}}{K_1}$ on the sign of the supply reaction is very small at more realistic values of the productivity parameter of oil λ lower than 0.1. The parameter λ is closely related to oil's income share (θ_{tR}), which has been way below 10% in the recent decades.[42]

4.3.1. Sign of the extraction reaction

We use a "ballpark" calibration (cf. Appendix B.1) as a reference point and as the basis for a sensitivity analysis of the monopolist's reaction to an ad valorem tax increase (starting at $\tau_2 = 0$) with respect to the more influential parameters σ and λ in Fig. 1.[43] The corresponding figure for a unit tax can be found in Appendix B.3. Parameter settings with incomplete extraction in equilibrium are shaded green. The black dotted curves indicate the borderlines between elastic and inelastic oil demand in period 1. Overall, postponement is a robust outcome of an announced future carbon tax increase in our model for $\lambda < 0.1$ and $\sigma < 1$, which are most consistent with empirical observations.

Extraction is necessarily accelerated for $\sigma \to \infty$ (cf. Appendix B.2). The change in production structure brought about by a rising elasticity of substitution and reflected in the change of the price elasticities of oil and the cross-price elasticity of capital

[39] In particular, $\frac{dR_1^*}{d\tau_2}|_{R_2}$ and $\frac{dR_2^*}{d\tau_2}|_{R_1}$ as well as $\frac{dR_1^*}{dR_2}$ and $\frac{dR_2^*}{dR_1}$ are defined in (A.6) and (A.7). For the unit tax case, the comparative statics would encompass exactly the same components.

[40] The asterisk "*" again indicates the monopolist's utility-maximizing extraction path (R_1^*, R_2^*).

[41] Due to the first effect on Ψ, an ad valorem tax may also lead to a decrease in R_1 without the asset motive. Moreover, since without an asset motive we would have $MV_2^{inc} = MR_2^{inc} = 0$ by (22), the influence of the ad valorem tax then would be restricted to R_1. These effects of a tax increase are also present in the case of complete extraction without an asset motive. For this, we would have Hotelling rule $(1+i_2)MR_1 + (1-\tau_2)\frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_1}|_{R_2} = (1-\tau_2)MR_2^{inc}$. A rise in τ_2 then creates the standard incentive to accelerate extraction because the net marginal resource revenue falls. But since the increase of the ad valorem tax also reduces the marginal value of R_1 in terms of its positive future oil demand influence via K_2, there is a counteracting supply incentive. Depending on the strength of each, postponement might occur even without the asset motive.

[42] For Cobb-Douglas production ($\sigma = 1$), λ equals θ_{tR}. For $\sigma < 1$, our simulations show that a realistic expenditure share of oil $\theta_{tR} < 0.1$ corresponds to $\lambda < 0.1$. According to data by World Bank Group (2016) the ratio of global oil rents to world GDP in the period 1970 to 2014 was between 0.5% (1970) and 5.5% (1980). Oil expenditures as a share of GDP peaked at 6.6% (1981) for the U.S. and at 5.3% for the OECD countries except the U.S. (cf. Fig. B.1 in Appendix B.1).

[43] For the case of complete extraction the supply-side reaction to a tax increase (ad valorem or unit tax) is monotonic in the tax rate (cf. Appendix A.6). As the case of incomplete extraction is, in contrast, a two-dimensional problem, we can not formally show this, but in all observed numerical examples the extraction reaction to a tax increase also turns out to be monotonic in the tax rate.

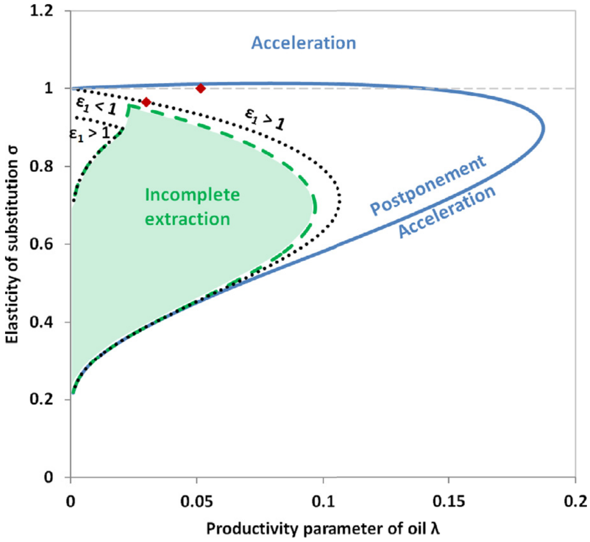

Fig. 1. Zones of acceleration and postponement of extraction over the elasticity of substitution σ and the productivity parameter of oil λ for an ad valorem tax. The red dots indicate the reference calibration and the corresponding Cobb-Douglas case of Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

demand prevents postponement of extraction for sufficiently high σ.[44] For $\sigma > 1$, postponement is only possible if the monopolist accounts for her influence on the capital dynamics and if $\frac{dK_2}{dR_2} < 0$ (cf. Appendix B.2). In contrast, when approaching the case of Leontief production ($\sigma = 0$), oil as the scarcest factor increasingly dominates production ($R_t < L_t$, capital was chosen to be always abundant) and extraction turns complete again. Given that marginal oil revenue rises and that the asset motive simultaneously becomes vanishingly small ($\frac{di_2}{dR_2} \to 0$ for $\sigma \to 0$), extraction will necessarily be accelerated for $\sigma \to 0$ (cf. numerator of (23)). An increase of λ has two effects. First, it raises the marginal resource revenue MR_t and the monopolist's losses via the carbon tax increase (contributing to acceleration). Second, when rising beyond a threshold which depends on the ratio of factor endowments it decreases the complementarity between both factors and, therefore, the postponement incentive.

4.3.2. *Magnitude of the extraction reaction*

To assess the magnitude of the postponement effect, in the following we relate it to the effect on the climate policy reaction of endogenizing the interest rate for competitive oil supply as in van der Meijden et al. (2015), to the corresponding effect for monopoly, and to the magnitude of the standard acceleration outcome. Table 1 gives an overview over the levels and changes of present extraction R_1 and the interest rate i_2 for the introduction of a future ad valorem tax which corresponds to 100$ per ton of carbon (cf. Appendix B.1), that is, relative to a tax of zero. We compare the model results to those of different alternative oil market structures: partial equilibrium versions ("PE") for competition and monopoly with a fixed exogenous capital stock K_2 and interest rates i_1, i_2 and for general equilibrium ("GE") the cases competition, a monopoly which neglects the asset motive in (19), and the benevolent monopolist with asset motive.[45]

The Cobb-Douglas case ($\sigma = 1$) in Table 1 features the same output level and, hence, the same implied length of period 1, as the reference setting.[46] For both, "Ref" and "CD", the step from PE competition (A) to GE competition (B), where savings, interest rates and oil demand curves are allowed to change endogenously (cf. van der Meijden et al. (2015)), only leads to a slight adjustment of the increase in present extraction R_1 due to the introduction of climate policy. Similarly, for an oil monopolist

[44] Thus, technical change in the form of an increase in the elasticity of substitution can increase the possibility that a future carbon tax will accelerate oil extraction and undermine mitigation goals. In contrast, a better substitutability of oil is often seen as necessary to overcome the dependency of economic growth on fossil resources, and to make climate change mitigation compatible with economic growth in the long run.

[45] We are also trying to compare the (small) effect of endogenizing the interest rate (and the capital stock) for a monopoly without asset motive to the small size of this effect for competition as shown in van der Meijden et al. (2015) in contrast to the more significant effect of the asset motive. To ensure this comparability, in (C) we construct a close PE counterpart of the GE monopoly without asset motive (D) by keeping the same decision rule (like van der Meijden et al. (2015) do for perfect competition), in this case (19) without the asset motive terms, and by fixing K_2, i_1, and i_2. Also, for comparability of PE and GE, the levels of K_2, i_1, i_2, and all other variables in the pre-policy state are identical in the respective PE and GE variants of competition ((A), (B)) and monopoly without asset motive ((C), (D)).

[46] The first-period output of $F_1 = 3056$ for the full model (E) in the reference case and the Cobb-Douglas setting corresponds to approximately 38.4 years multiplied by US $79.6 trillion world GDP (cf. CIA, 2014). Cf. Appendix B.1 for calibration details. The parameter λ in the Cobb-Douglas case should be higher than in the reference case anyway to reach a similar income share of oil of $\theta_{1R} = 0.0348$. But then the output levels and the lengths of period 1 would still differ by some 13 percent.

Table 1
Levels and changes of R_1 and i_2 for a future ad valorem tax τ' that corresponds to $100\,\frac{\$}{t_C}$ in different oil market structures for the reference calibration ("Ref") and the corresponding Cobb-Douglas case ("CD"): partial equilibrium ("PE") and general equilibrium ("GE") competition and monopoly ((A)-(D)) and the full general equilibrium monopolist with asset motive (E).

		τ	(A)PE comp.	(B)GE comp.	(C)PE mon.	(D)GE mon.	(E)GE mon.w/assets
i_2	Ref	0	3.0710	3.0710	2.1895	2.1895	**2.9724**
		τ'	3.0710	3.0673	2.1895	2.1895	**2.9884**
	CD	0	3.1541	3.1541	3.0752	3.0752	**3.1230**
		τ'	3.1541	3.1506	3.0752	3.0730	**3.1236**
R_1	Ref	0	0.2001	0.2001	0.2499	0.2499	**0.2222**
		τ'	0.2011	0.2011	0.2499	0.2499	**0.2193**
	CD	0	0.2028	0.2028	0.2165	0.2165	**0.2087**
		τ'	0.2036	0.2035	0.2169	0.2168	**0.2086**
$\frac{\Delta R_1}{R_1}$	**Ref**		**+0.546%**	**+0.523%**	**0%**	**0%**	**−1.283%**
	CD		**+0.366%**	**+0.344%**	**+0.186%**	**+0.157%**	**−0.055%**

who neglects her influence on the capital returns, the step from PE (C) to GE (D) affects the climate policy reaction only slightly, as we see in the "CD" case. For the reference calibration in (C) and (D), a demand elasticity in period 1 of $\epsilon_1 = 1$ implies in equilibrium $MV_2 = MR_2 = MR_1 = 0$, so that the reaction to an ad valorem tax policy is exactly zero anyway. In both, (C) and (D), the magnitude of the climate policy reaction differs from the competitive cases (A) and (B), because the monopolist's different FOC ((19) without the asset motive) implies a different pre-policy equilibrium and a different adjustment to the tax increase.[47] Finally, taking into account the capital asset motive leads to a significant overall reduction of present extraction by approximately 1.3 percent. This value is at the upper bound of observed magnitudes and it rises almost proportionally with the tax rate. The effects for Cobb-Douglas production or the zone of incomplete extraction are smaller.[48] Even though the magnitude of postponement may not seem huge, it is considerable relative to the acceleration results discussed in previous literature. It is reasonable to expect smaller postponement effects for a more competitive market structure. The results of the discussion regarding a competitive fringe (cf. Section 5.2) support this view.

5. Discussion

5.1. Elasticity of oil demand

We now discuss the robustness and relevance of our results with respect to the empirics on the elasticity of oil demand and the assumptions regarding the market structure.

We obtained our results while allowing the monopolist to leave a part of the oil in the ground, following Stiglitz (1976) and Tullock (1979). This naturally puts a lower bound to the oil demand elasticity in period 1 in the according parameter settings of the CES production function (cf. the area of incomplete extraction in Fig. 1). The monopolist can still extract in a slightly inelastic area of the present demand curve, i.e. with $MR_1 < 0$, as long as the asset motive $\frac{\partial i_1}{\partial R_1} s_{0E}$ is positive (leading to $MV_1 \geq 0$) and/or the effect of R_1 on the future income streams via capital accumulation $\Psi = [(1-\tau)\frac{\partial p_2}{\partial K_2} R_2 + \frac{\partial i_2}{\partial K_2} s_{1E}] \frac{dK_2}{dR_1}|_{R_2}$ (cf. 20 and 21) is positive. This is the case in the area circumscribed by the black dotted curve in Fig. 1. But still, the demand elasticity in the numerical examples is not far from one from both sides.

Despite only slightly inelastic or elastic present demand our results are relevant and largely consistent with empirical evidence because of the very long time horizon of our model (period 1 corresponds to 38.4 years in the reference calibration). The empirical evidence on the very long term demand elasticity is quite unclear. There is a large number of empirical estimates for a "long-term" demand elasticity for crude oil or gasoline in the range between 0.16 and 1.16 (cf. Brons et al. (2008), Hamilton (2009), and Labandeira et al. (2017)). But, as Davis and Kilian (2011) and Sen and Vollebergh (2018) point out, these estimates are biased towards zero because of the simultaneity problem of endogenous prices and quantities. When controlling for this bias, Davis and Kilian (2011) find elasticities four times larger, and Sen and Vollebergh (2018) find coefficients of tax effects on energy demand over three times larger than with the bias. In addition, "long-term" in the aforementioned studies refers to time periods of a few years to at most ten years, depending on the identification strategy, within which aspects of the demand structure can adjust, like vehicle choice. On our much longer time scale demand will be significantly more elastic as additional substitution options for oil and efficiency increases become available through technological developments. But "standard econometric models based on historical data do not allow the prediction of such long-run effects" (Davis and Kilian, 2011). Furthermore, recent studies point to empirical evidence on the rather high long-term substitutability between fossil energy resources and capital/labor (cf. Hassler et al. (2012)) or clean energy sources (cf. Papageorgiou et al. (2017)). This also supports our choice of a rather high substitution elasticity σ close to one and a demand elasticity ϵ_1 close to or even above one in the very long term.

[47] This is also true for Cobb-Douglas production ($\sigma = 1$) as the monopolist is accounting for $\frac{\partial p_2}{\partial K_2}\frac{dK_2}{dR_2}$ (cf. (15)) in (19) and future demand is not iso-elastic.

[48] Note that the pre-policy equilibrium in (E) is also slightly different to (C) and (D).

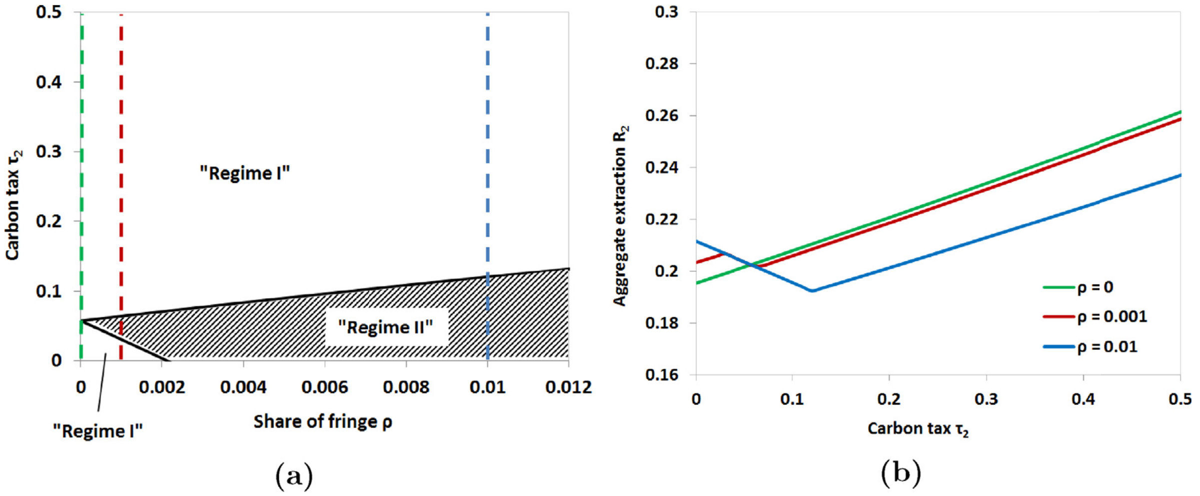

Fig. 2. a) Supply regimes over τ and ρ, b) Aggregate extraction over increasing carbon tax τ_2. The dashed lines in the τ-ρ-space at different values ρ in Fig. 2 correspond to the curves in the right panel. Further parameters: $\beta = 0.3, \eta = 2, s_{0E} = 20, s_{0I} = 180$, yielding $K_1 = 200, \bar{S} = 1$.

5.2. *Dampened market power: competitive fringe*

Although the OPEC's market power as judged by its share in the global oil stock is certainly high, pure monopoly is a strong assumption.[49] In this section we introduce a competitive fringe with a share ρ of the global oil stock $\bar{S}$ to show how the channel for extraction postponement is affected.[50] This oil is evenly distributed over a mass of size 1 of small, price-taking firms owned by households in country *I*.[51] The monopolist ("M") and the fringe ("F") exhaust their oil stocks over both periods, so that we have $R_1^M + R_2^M = S^M = (1-\rho)\bar{S}$ and $R_1^F + R_2^F = S^F = \rho\bar{S}$. The relationships between *aggregate* oil supply $R_t = R_t^M + R_t^F$, factor prices, and capital accumulation in the conditional market equilibrium remain unchanged (cf. Appendix C.1 for details).

Proceeding analogously to Section 3 leads to Hotelling condition

$$(1+i_2)\left[p_1 + \frac{dp_1}{dR_1^M}R_1^M + \frac{di_1}{dR_1^M}s_{0E}\right] = \widetilde{p}_2 + \frac{d\widetilde{p}_2}{dR_2^M}R_2^M + \frac{di_2}{dR_2^M}s_{1E} \tag{26}$$

Only now the monopolist, still a Stackelberg leader, accounts for the fringe's supply response in the terms $\frac{dp_t}{dR_t^M}$ and $\frac{di_t}{dR_t^M}$ (cf. Appendix C.3). The response is implicitly characterized by the competitive Hotelling condition $(1+i_2)p_1 = \widetilde{p}_2$. Two polarized supply regimes arise delimited by a threshold size of the fringe $\widehat{\rho}$, depending on whether equilibrium market prices drive the fringe to a corner solution.

Regime I "Corner Solution": For $\rho < \widehat{\rho}$, the monopolist chooses to drive the fringe into a corner solution. We either have $(1+i_2)p_1(R_1^M + S^F) > (1-\tau)p_2(R_2^M)$ or $(1+i_2)p_1(R_1^M) < (1-\tau)p_2(R_2^M + S^F)$,[52] and the fringe does not respond at all so that $\frac{dp_t}{dR_t^M} = \frac{dp_t}{dR_t}$ (cf. (10), (15)), and $\frac{di_t}{dR_t^M} = \frac{di_t}{dR_t}$ (cf. (11), (16)). The reasoning and all parts of (26) resemble (19) except for the infra-marginal units $(R_t^M \neq R_t)$.

Regime II "Interior Solution": For $\rho \geq \widehat{\rho}$, the monopolist prefers an interior solution for the fringe, so that $(1+i_2)p_1 = (1-\tau)p_2$ holds for the *overall* market equilibrium.[53] The fringe (locally) compensates for changes in monopolistic supply so that $\frac{dp_t}{dR_t^M} = 0$ and $\frac{di_t}{dR_t^M} = 0$, and (26) boils down to the competitive Hotelling rule.[54]

We now focus on the fringe's implications for the postponement channel via the capital asset motive. An analysis of all climate policy effects in the competitive fringe setting is beyond the scope of this paper and left for future research. We make two key observations.

[49] The OPEC claims in Organization of the Petroleum Exporting Countries (2017) to have a share of global proven oil reserves of approx. 82%.
[50] We focus on the case of complete extraction here to keep the exposition short.
[51] With symmetric homothetic preferences, assuming a third group of countries would be equivalent.
[52] Which corner solution arises, depends on the deviation from the competitive path implied by the monopolist's supply motives, in particular the asset motive (cf. Marz and Pfeiffer, 2015).
[53] In this case, the competitive equilibrium implies the smallest, incentive-compatible deviation from the monopolist's preferred aggregate supply path.
[54] Since in regime II the present value of oil stocks for both, the monopolist and the fringe, is fixed in the competitive market equilibrium, there is also no unique optimal intertemporal distribution of oil for the monopolist and no unique geographic distribution of oil quantities in either period.

1. Under regime I the monopolist may postpone or accelerate extraction depending on the asset motive, just as in the standard setting (cf. Section 4). Under regime II, climate policy yields an acceleration of aggregate extraction ("Green Paradox").
2. Since $\widehat{\rho}$ depends on the tax level, a sufficiently strong tax increase under regime II may induce a switch to regime I and nevertheless postpone aggregate extraction (cf. Fig. 2) similarly to the pure monopolist ($\rho = 0$, green curves).

A larger share of the fringe ρ is more likely to suspend the asset motive and the postponement channel and to lead to regime II (cf. Appendix C.3).[55] Due to our two-period, finite time horizon setting, there is no gradual fading out of market power, as it would be plausible, but unrealistically polarized regimes. However, the monopolist's "latent" market power under regime II is reflected by the fact that the critical share $\widehat{\rho}$ can be surpassed at a higher carbon tax τ_2 and the capital asset based transmission channel is still relevant at higher ρ. If the monopolist prefers to postpone extraction, then the carbon tax provides counteracting supply incentives for the monopolist and the fringe, making a corner solution of the fringe, i.e., a switch to regime I, more probable.[56]

6. Conclusion

Climate policy not only threatens fossil energy revenues, but it also has implications for the capital market, as the recent stranded assets debate suggests. By accounting for the capital market dimension as a second pillar of an oil monopolist's income and oil supply policy, we identify a new transmission channel of climate policy in general equilibrium. In addition to oil rents, the monopolist considers her influence on returns on petrodollar-financed capital assets ("capital asset motive") which arises from the complementarity of oil and capital. Due to the introduction or increase of a future carbon tax which devaluates the oil asset, the exporting country increases future capital assets to smooth consumption. This strengthens the asset motive and can postpone extraction even without extraction costs and/or oil substitutes in contrast to large parts of the literature on an unintended acceleration of extraction ("Green Paradox"). Postponement particularly depends on the sensitivity of the two income pillars to the carbon tax. This is determined 1) by the strength of the savings reaction, 2) by the value of oil in production, and 3) by the strength of the link between the capital market and the oil market. In the numerical analysis, postponement occurs for a wide range of parameter settings. For the reference calibration, present extraction drops by 1.28 percent with the introduction of an ad valorem tax which corresponds to 100 dollars per ton of carbon. By contrast, it changes by 0 percent if the monopolist neglects the new capital asset channel and increases by 0.52 percent for a competitive oil market. As another parameter setting (with Cobb-Douglas production) illustrates, the effect of endogenizing the interest rate for an oil monopoly in general equilibrium per se (i.e., without accounting for the new capital asset motive) is, by contrast, quite small (−0.03 percent of present extraction), similarly to the case of a competitive oil market as examined in van der Meijden et al. (2015). This seems plausible since oil's income share in global GDP is fairly small, too. The role of oil rents for the income of OPEC countries is much larger. An impact of climate policy on oil rents, thus, may trigger large relative shifts in savings and, given that oil supply (still) influences the returns on these assets in the future, more significant adjustments of the extraction schedule than in the competitive case.

Overall, market power in the global oil market can be of fundamental importance for the effects of climate policies. To put the extreme assumption of monopoly power into perspective, we briefly discuss a setting with a competitive fringe with an exhaustible oil stock. Due to our two-period setting, this leads to polarized supply regimes with, in principle, quite different supply responses. But for a sufficiently strong tax increase the monopolist may prefer to switch supply regimes, and again to more openly use her market power thereby even inducing a postponement of overall extraction.

Future research with regard to the capital asset motive could account for the internal dynamics of OPEC, for instance in a more oligopolistic market structure. To examine the implications of the asset motive in a setting with clean or dirty substitutes and/or a limit pricing regime, which is beyond the scope of the present framework with a finite time horizon, is another potential avenue for future research. Finally, due to the redistribution of resource rents between countries and the induced savings reactions, the future share of the oil-rich country in the global capital stock increases, raising the potential capital market influence of "petrodollars" as a topic for future research.

Acknowledgements

We gratefully acknowledge financial support from the German Federal Ministry of Education and Research (Project No. 01LA1120A: "Assessing the Green Paradox") and by the Friedrich Ebert Foundation. We also greatly appreciate the helpful comments and suggestions by Wolfgang Buchholz, Ken Gillingham, Wolfgang Habla, Niko Jaakkola, Ngo Van Long, Pietro Peretto, Karen Pittel, Michael Rauscher, Alex Schmitt, Suphi Sen, Daniel Spiro, Christian Traeger, Gerard van der Meijden, Rick van der Ploeg, Cees Withagen, and the anonymous referees, as well as by the participants of the FSR Climate 2015 conference (Florence), SURED 2016 (Banyuls-sur-mer), the IAEE 2016 conference (Bergen), the pre-EAERE workshop on Stranded Assets 2017 (Athens) and various seminars at the ifo Institute.

[55] Time consistency is not an issue due to the monopolist's role as Stackelberg leader and two periods.

[56] Before a rising ad valorem carbon tax reaches unity, the switch to regime I must necessarily occur, even for arbitrarily high shares of the fringe ρ (cf. Fig. C.1 in Appendix C.3), because the post-tax oil price $\widetilde{p}_2$ approaches zero whereas the marginal resource value of the monopolist MV_2 does not due to her asset motive.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jeem.2019.102263.

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